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LIFE CYCLE MANAGEMENT

# Application of LCSA to used cooking oil waste management

**Elisabet Vinyes · Jordi Oliver-Solà · Cassia Ugaya · Joan Rieradevall · Carles M. Gasol**

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**Abstract**
*Purpose* Used cooking oil (UCO) is a domestic waste generated as the result of cooking and frying food with vegetable oil. The purpose of this study is to compare the sustainability of three domestic UCO collection systems: through schools (SCH), door-to-door (DTD), and through urban collection centres (UCC), to determine which systems should be promoted for the collection of UCO in cities in Mediterranean countries.
*Methods* The present paper uses the recent life cycle sustainability assessment (LCSA) methodology. LCSA is the combination of life cycle assessment (LCA), life cycle costing, and social life cycle assessment (S-LCA).
*Results and discussion* Of the three UCO collection systems compared, the results show that UCC presents the best values for sustainability assessment, followed by DTD and finally SCH system, although there are no substantial differences between DTD and SCH. UCC has the best environmental and economic performance but not for social component. DTD and SCH present suitable values for social performance but not for the environmental and economic components.
*Conclusions* The environmental component improves when the collection points are near to citizens' homes. Depending on the vehicle used in the collection process, the management costs and efficiency can improve. UCO collection systems that carry out different kind of waste (such as UCC) are more sustainable than those that collect only one type of waste. Regarding the methodology used in this paper, the sustainability assessment proposed is suitable for use in decision making to analyse processes, products or services, even so in social assessment an approach is needed to quantify the indicators.

Defining units for sustainability quantification is a difficult task because not all social indicators are quantifiable and comparable; some need to be adapted, raising the subjectivity of the analysis. Research into S-LCA and LCSA is recent; more research is needed in order to improve the methodology.

**Keywords** Life cycle assessment (LCA) · Life cycle costing (LCC) · Social assessment · Sustainability

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E. Vinyes (✉) · J. Oliver-Solà · J. Rieradevall · C. M. Gasol
SosteniPrA (ICTA-IRTA-Inèdit), Institute of Environmental Science and Technology, Universitat Autònoma de Barcelona (UAB),
08193 Bellaterra,
Cerdanyola del Vallès, Spain
e-mail: elisabet.vinyes@gmail.com

J. Oliver-Solà · C. M. Gasol
Inèdit Innovació S.L., Universitat Autònoma de Barcelona (UAB), Research Park, Carretera de Cabrils km. 08348 Cabrils, Barcelona, Spain

C. Ugaya
Universidade Tecnologica Federal do Parana (UTFPR), Itapicuru, Avda. Sete de Setembro,
3165 Rebouças Curitiba, PR, Brazil

J. Rieradevall
Engineering School (ETSE), Universitat Autònoma de Barcelona (UAB),
Campus of the UAB, Bellaterra (Cerdanyola del Vallès),
08193 Barcelona, Catalonia, Spain

## 1 Introduction

Used cooking oil (UCO) is a domestic waste generated as the result of cooking and frying food with vegetable oil and is classified by the European Waste Catalogue (EC/532/2000) with European Waste Catalogue number 200125. A large amount of UCO is removed through the sewage

system causing environmental and economic problems. In Mediterranean countries, it is estimated that 3–5 kg of UCO is generated per person per year (Talens Peiró et al. 2008). The collection of domestic oil depends on several key factors, such as: economic profit to cover economic costs of the waste management system, environmental awareness by local authorities, the interest in promoting environmental measures, and social benefits such as job creation.

The lack of standardised collection systems implies low recuperation rates of UCO waste of around 11.98 % (Talens Peiró et al. 2008). Currently, a possible way of recycling the waste generated from UCO is the production of biodiesel, which can minimise this waste and also generate renewable energy. With adequate incentives, nearly 70 % of UCO could be recovered to produce biodiesel (Math et al. 2010). The recent concerns for sustainability, environment and raw material costs have made the use of waste frying oils attractive to the biodiesel industry (Zhang et al. 2003). Until now, UCO as a raw material to produce biodiesel has been analysed in depth from an economic and environmental point of view (Math et al. 2010). (Talens Peiró et al. 2010; Morais et al. 2010; Felizardo et al. 2005; Zhang et al. 2003).

Life cycle sustainability assessment (LCSA) is the combination of life cycle assessment (LCA), life cycle costing (LCC) and social life cycle assessment (S-LCA; Klöpffer and Udo de Haes 2008; Heijungs et al. 2010; Venturini et al. 2010). The maturity of methods and tools is different for the three sustainability dimensions (LCA, LCC and S-LCA), while the environmental dimension is quite well developed today, social and sustainability indicators and evaluation methods still need further research. Social assessment is viewed by some authors (Klöpffer and Ciroth 2011; Hunkeler 2006) as a complement to LCA and LCC and as a third component of measuring sustainable development, defined by Brundtland (1987) as a "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". Although research into S-LCA is recent and less mature than LCA and LCC, some methodological guides have already been published as United Nations Environment Programme/The Society for Environmental Toxicology and Chemistry (UNEP/SETAC 2009) guide; however, no specific methodology on how to integrate LCA, LCC and S-LCA has been established so far. The case studies published are few and the methodology is still being developed (Klöpffer 2006; Dreyer et al. 2006; Hauschild et al. 2008).

### 1.1 Objective

The present paper aims to assess the sustainability of three UCO collection systems in a neighbourhood of 10,000 inhabitants in Barcelona, Catalonia (North-East Iberian Peninsula), in order to determine which systems should be promoted for UCO collection in the cities of Mediterranean countries, and also to improve the low UCO recuperation rates due a lack of standardised collection systems. The study aims to evaluate and compare the impact of the UCO collection service, but not to quantify the impacts of generating UCO. The UCO collection systems compared are: door-to-door (DTD), schools (SCH) and urban collection centres (UCC).

## 2 Methodology

The methodology selected in this paper is LCSA. According to Venturini et al. (2010), LCSA is the combination of LCA, LCC and S-LCA without formal weighting between them. For LCSA, weighting problem exists on at least two levels: weighting of individual indicators within each of the three sustainability dimensions, and weighting among the three dimensions of sustainability: environmental, economic and social (Finkbeiner 2010). Sustainability of human–environment systems is determined through three main characteristics: resilience to disturbances, both natural and anthropogenic, desirability to human societies, and temporal and spatial scale boundaries (Mayer 2008). According to Venturini et al. (2010), sustainability assessment needs a multi-criterial approach and different issues need to be considered and evaluated.

### 2.1 Environmental assessment

LCA has been applied in environmental assessment. All data, except the collection type, used were from ecoinvent database v.2.2. The impact categories included in the study are mid-point indicators, according to CML 2001 (Guinée 2001). In this method, the environmental flows were assigned by multiplying them by the corresponding characterization factor for each impact category. The impact categories considered and their units are: abiotic depletion (kg Sb eq), acidification (kg $SO_2$ eq), eutrophication (kg $PO_4^{3-}$ eq), global warming (100 year; kg $CO_2$ eq), ozone layer depletion (kg CFC-11 eq), human toxicity (kg 1,4-DB eq), fresh water aquatic ecotoxicity (kg 1,4-DB eq), marine aquatic ecotoxicity (kg 1,4-DB eq), terrestrial ecotoxicity (kg 1,4-DB eq), photochemical oxidation (kg $C_2H_4$) and cumulative energy demand (MJ eq). Although there are normalisation factors, the optional steps of normalisation and weighting are excluded in the present study order to avoid subjectivity in the analysis. Calculations were performed in the software SimaPro 7.2 (ISO 14040 2006).

### 2.2 Economic assessment

LCC has been applied to do the economic assessment, although there are some discussions on whether it should or not be included in an LCSA (Klöpffer and Ciroth 2011). According to UNEP/SETAC Guidelines for Social Life Cycle Assessment of Products, Environmental LCC is defined as: “An assessment of all costs associated with the life cycle of a product that are directly covered by any one or more of the actors in the product life cycle (e.g., supplier, manufacturer, user or consumer, or End of Life actor) with complementary inclusion of externalities that are anticipated to be internalised in the decision-relevant future (Hunkeler et al. 2008)”. Environmental LCC can be used as a weighting method for an LCA. It allows to reduce the number of decision variables into a manageable amount and to better communicate results from environmental studies. (Carlsson Reich 2005). LCA studies the environmental impact of a system, while LCC is a tool for analysing the economic effects of the LCA; however, using LCC in combination with LCA can provide some difficulties, the main problem of this aggregation is to make sure that no double counting takes place (Carlsson Reich 2005).

Conferring to the characteristics of the three collection systems studied and the available data, the LCC applied in this study includes the following internal and external costs. The internal costs considered are: containers manufacture, representative salary of employer categories and fuel cost related to transport stages. The external cost considered is the cost of mitigating $CO_2$ emissions, according to the international $CO_2$ market, converting the environmental global warming impact into monetary values (Gasol et al. 2007; Finnveden et al. 2006; European Community 2003). As the systems under study are located in Catalonia, the currency selected is the Euro (€) and assumed costs are valid for the year 2011. To avoid double counting, $CO_2$ emissions costs have been included in LCC calculation as an external cost, but these costs have not been considered in the LCC scoring process, because $CO_2$ emissions have already been scored in LCA.

### 2.3 Social assessment

S-LCA can in many regards be seen as a parallel to the environmental life cycle assessment, but rather than focusing on environmental impacts, the S-LCA focuses on social impacts of products, processes, services or systems in principle throughout their life cycle (Jørgensen et al. 2010a, b). Measuring social impacts needs a degree of complexity. One fundamental issue seems to be which impact categories to include in the assessment and how to measure social impacts because the perception of social, impacts is very variable (Jørgensen et al. 2008; Benoît et al. 2010). Research into S-LCA is recent and less mature than LCA and LCC, the methodology is still being developed. Some methodological guides to select social indicators have already been published as UNEP/SETAC guide; however, no specific methodology has been established so far and the published case studies are few (Klöpffer 2006; Hauschild et al. 2008).

In S-LCA, not only quantitative data is used, semiquantitative and qualitative data have also been integrated according to UNEP/SETAC guidelines (2009). When conducting an S-LCA, it is important to address the quality and integrity of the data to ensure the reliability and validity of the results and to be able to draw the right conclusions. The geographical location is of major importance in S-LCA. The UNEP/SETAC methodology has listed indicators according to five stakeholder categories: worker, consumer, local community, society and companies throughout the life cycle of the product. The selected social indicators in this study, according to the functional unit, the data and information available, the geographic location, and the characteristics and limitations of the three collection systems studied, are: total employees, total working hours, employees with disabilities, employees with higher education, employees with basic education, equal opportunities (sex), equal opportunities (degree of disability), children’s environmental education, local employment, public commitments to sustainability issues and contribution to economic development. Some indicators have been modified from the UNEP/SETAC guidelines in order to consider all the relevant social aspects that are involved in the three systems studied, for example: children’s environmental education and equal opportunities for employees with degree of disability or special needs. The data used to calculate social indicators have been obtained from entities and organisations that are currently applying these UCO collection systems to Catalonia (Waste Agency of Catalonia 2011; LABORIS 2011; CREANT 2011).

### 2.4 System description

The three UCO collection systems analysed are the following:

(a) *DTD system*: UCO is stored by citizens in their homes in a container with a capacity of one litre. Once a month, a special collection service (carried out by workers with a degree of disability) collects the containers full of UCO from houses and returns a new clean container. The full containers collected are transported by van to a centre called “Special Working Centre” (SWC) where UCO is deposited in 1,000-l containers, in order to be stored and transported later to a biodiesel plant (BDP) in a tanker. The empty collection containers are washed at the SWC with an industrial

dishwasher in order to be reused. The employees that work at the SWC also are people with special needs that present a degree of physical or intellectual disability. Note that citizens that want to use DTD system must be registered in the service and must adapt to the collection schedule.

(b) *SCH system*: Schools enable a space in the centre in order to collect UCO. Students bring 1-l containers full of UCO directly from their homes and return home with a clean empty container. Once a month, containers full of UCO are collected from schools by authorised transport service and containers are transported by van to an SWC, where the UCO is deposited in 1,000-l storage containers, in order to be transported later to a BDP in a tanker. The empty containers are washed to be reused in the same way as DTD system, with an industrial dishwasher. The employees that work at the SWC are people with a degree of disability.

(c) *UCC system* Urban Collection Centres collect different municipal waste in small quantities (batteries, electronic devices, scarp, detergents, solvents, etc.) so people who are interested in collecting UCO at home can bring it to these collection points. The study assumes that users bring 1-l containers to UCC at an average frequency of once a month regardless of the amount of UCO collected in them. UCO is stored in 1,000-l storage containers. Users are responsible for washing and reusing the empty containers at home. When the 1,000-l storage containers are full, a tanker transports the UCO to a BDP.

The study gives emphasis to the motivation that each system generates to the citizens and how this affects to the amount of UCO collected. The production of biodiesel is not part of the boundaries of the study (Fig. 1), because the study wants to evaluate the impact and sustainability of the UCO collection systems existing in Catalonia, not the amount of biodiesel produced from UCO collected. This study does not want to measure the impacts avoided by not distorting the results of the impact of UCO collection services, because it does not know for sure if all the UCO collected will be used to produce biodiesel, and therefore the best system will be the one that collects more UCO with less impact, less costs and contributes better socially.

## 2.5 Functional unit

The functional unit of this study is to collect the UCO generated in a neighbourhood of 10,000 inhabitants for 1 year in the city of Barcelona considering the efficiency of the each collection system.

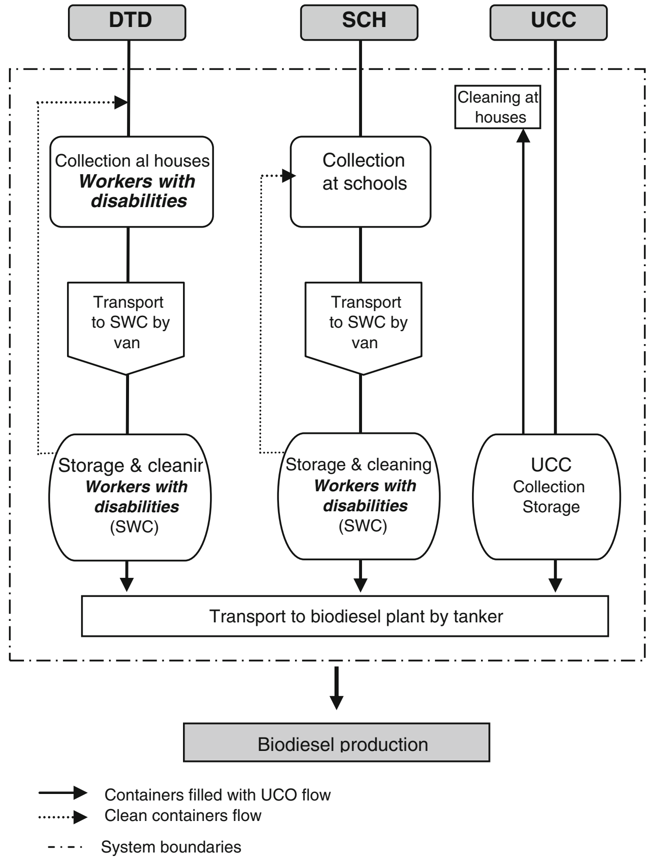



**Fig. 1** Description of UCO collection systems analysed

### 2.5.1 Reference flows

Even though the number of inhabitants considered in the functional unit is the same, the amount of UCO collected for each collection system studied (DTD, SCH and UCC) is different. This can be explained because these collection systems present different efficiencies due to the motivation that each collection system generates to citizens. For example in the case of the UCC and SCH, the motivation is higher because citizens or students can bring UCO in the collection centre as many times as they want and any citizen can bring UCO; however in DTD, citizens need to be registered to receive the service at home and UCO collection process is subject to a schedule and a fixed frequency.

According to the data from Waste Agency of Catalonia (2011), the potential UCO generated by 10,000 inhabitants should be 37,750 l per year. In is this study, considering that the UCO collection systems analysed present different efficiencies due to the motivation created in the citizens, and according to real data obtained from some organisations that currently are developing UCO collection in Catalonia (LABORIS 2011; CREANT 2011; Waste Agency of Catalonia 2011) UCO collected and containers needed for each collection systems are the following:

– DTD has an efficiency of 57 %, collects 21,600 l of UCO and requires 2,025 collection containers
– SCH has an efficiency of 64 %, collects 24,000 l of UCO and requires 4,000 collection containers
– UCC has an efficiency of 67 %, collects 25,200 l of UCO and requires 2,100 containers

(see more details in Table 1).

The SCH system needs the highest number of collection containers because the frequency of UCO collection is lower, making it necessary for there to be a larger number of empty containers available to the users.

## 2.6 Allocation

UCC system collects different types of waste, so allocation of economic and social assessments has been performed in order to only consider social and economic inputs and outputs involved in UCO collection. The allocation has been calculated from the management cost associated with UCO collection, considering that UCO represents 4 % of the total waste collected (Waste Agency of Catalonia 2011).

## 2.7 Inventory

The following section presents environmental, social and economic data for the three collection systems under study.

**Table 1** Inventory of three UCO collection systems according to the functional unit

| Inputs | Units | DTD | SCH | UCC |
|---|---|---|---|---|
| UCO collected | Litres | 21,600 | 24,000 | 25,200 |
| Collection efficiency | % | 57 | 64 | 67 |
| Containers | | | | |
| Collection container | Number | 2,025 | 4,000 | 2,100 |
| Storage containers | Number | 22 | 24 | 25 |
| PP collection container | kg | 101 | 200 | 105 |
| HDPE storage container | kg | 259 | 288 | 302 |
| Transport to SWC | | | | |
| Transport to storing centre | kg km | 1,724,612 | 2.129,150 | 0 |
| Cleaning stage | | | | |
| Plastic dishwasher | kg | 1 | 1 | 1 |
| Steel dishwasher | kg | 6 | 6 | 5 |
| Soap cleaning | kg | 51 | 50 | 34 |
| Water cleaning | l | 12,150 | 12,000 | 14,238 |
| Energy | kWh | 633 | 625 | 261 |
| Transport to BDP | | | | |
| Transport to biodiesel plant | kg km | 8,566.04 | 10,575.36 | 11,659.33 |

Table 1 shows the data of the inventory in relation to the functional unit.

*Collection and storage container stage* The collection containers and storage containers used have the same characteristics for the three collection systems. The collection containers have a capacity of 1 l, are made of propylene and have an average lifetime of 2 years. Storage containers have a capacity of 1,000 l, are made of high density polyethylene and have a lifetime of 5 years.

*UCO transport* In DTD and SCH systems, the distance of the transport collection stage is assumed to be 5 km. In the UCC system, it is assumed that there is no transport stage between the collection and storage stages, because the collection centre is near to the citizens' houses and can be reached on foot. To transport UCO to the BDP, the same distance has been assumed for the three systems, 100 km.

*Cleaning stage* DTD and SCH systems integrate a cleaning service, once UCO collection containers have been emptied these are washed in industrial dishwashers. At UCC, the cleaning stage is the citizens' responsibility. In this study, it has been considered that 60 % of citizens use dishwashers and 40 % wash by hand (data for Spain, BALAY 2011).

## 2.8 Sustainability assessment

As is mentioned above, LCSA is the combination of LCA, LCC and S-LCA without formal weighting. LCSA requires a multi-criteria evaluation to address the balance of the indicators as well as the weighting between them. In order to relate social indicators and its impact to the functional unit and to restrict social indicators proposed to a manageable and comparable number, in this study, it has been assumed that each dimension (environmental, economic and social) has the same weight, but the indicators chosen have different percentages of contribution to the global sustainability of the systems studied. It has been distinguished between positive and negative indicators, according to their contribution to sustainability in accordance with the characteristics of the systems studied. Negative indicators are those that high values have a negative contribution to sustainability (economic and environmental indicators) and positive indicators are those that have a positive contribution to sustainability (social indicators).

In this study, to apply multi-criteria approach, the indicators used in LCA, LCC and S-LCA have been grouped in three sustainability factors (SF): SFenviron., SFcosting and SFsocial. The methodology used to calculate the SF is based

on the integration described by Muñoz Ortiz (2006) but in this study, social component has also been considered. The stages of SF calculation are described below:

1. Once obtaining the results of LCA, LCC and S-LCA, the values obtained for all indicators are transformed into contribution percentages. These percentages are calculated by comparing the values that each collection system have obtained for the same indicator, so the collection system that has the highest indicator value has a contribution of 100 % and the rest of the systems obtain a proportional percentage (Table 2).
2. Scores from 1 to 5 are given to each indicator according to the percentage of contribution assigned. To score the contribution of indicators to sustainability, a differentiation has been made between *negative indicators* (greater percentage of contribution means lower contribution to sustainability) as the case of economic and environmental assessment, and *positive indicators* (greater percentage of contribution means greater the contribution to sustainability) as the case of social assessment. For *negative indicators*, the scale of scores is defined as: 1 point for percentage contribution of 100–81 %, 2 points for 80–61 %, 3 points for 60–41 %, 4 points for 40–

**Table 2** Sustainability assessment

| | Results of LCA | | | | Contribution | | | Scores | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Units | DTD | SCH | UCC | DTD (%) | SCS (%) | UCC (%) | DTD | SCH | UCC |
| Environmental indicators (negative indicators) | | | | | | | | | | |
| Abiotic depletion | kg Sb eq | 55.07 | 69.06 | 44.73 | 80 | 100 | 65 | 2 | 1 | 2 |
| Acidification | kg $SO_2$ eq | 26.27 | 31.91 | 24.09 | 82 | 100 | 75 | 1 | 1 | 2 |
| Eutrophication | kg PO4 eq | 7.82 | 9.57 | 7.34 | 82 | 100 | 77 | 1 | 1 | 2 |
| Global warming (GWP100) | kg $CO_2$ eq | 6,875.35 | 8,510.98 | 5,651.11 | 81 | 100 | 66 | 1 | 1 | 2 |
| Ozone layer depletion (ODP) | kg CFC-11 eq | 0.0010 | 0.0013 | 0.0008 | 80 | 100 | 62 | 2 | 1 | 2 |
| Human toxicity | kg 1,4-DB eq | 2,549.25 | 3,111.33 | 2,524.86 | 82 | 100 | 81 | 1 | 1 | 1 |
| Fresh water aquatic ecotoxicity | kg 1,4-DB eq | 1,144.25 | 1,381.71 | 1,119.02 | 83 | 100 | 81 | 1 | 1 | 1 |
| Marine aquatic ecotoxicity | kg 1,4-DB eq | 2,294,869.64 | 2,798,558.05 | 2,283,038.82 | 82 | 100 | 82 | 1 | 1 | 1 |
| Terrestrial ecotoxicity | kg 1,4-DB eq | 54.93 | 58.26 | 45.55 | 94 | 100 | 78 | 1 | 1 | 2 |
| Photochemical oxidation | kg C2H4 | 2.03 | 2.45 | 2.00 | 83 | 100 | 82 | 1 | 1 | 1 |
| Energy consumption | MJ eq | 138,146.16 | 172,189.35 | 138,708.29 | 80 | 100 | 81 | 2 | 1 | 1 |
| | | | | | Total score | | | 14 | 11 | 17 |
| Economic indicators (negative indicators) | | | | | | | | | | |
| | € | 37,734.78 | 6,725.18 | 3,396.85 | 100 | 18 | 9 | 1 | 5 | 5 |
| | | | | | Total score | | | 1 | 5 | 5 |
| Social indicators (positive indicators) | | | | | | | | | | |
| Total employees with higher education | Workers | 9 | 5 | 2 | 57 | 30 | 13 | 3 | 2 | 1 |
| Total employees with basic education | Workers | 46 | 15 | 12 | 68 | 22 | 10 | 4 | 1 | 1 |
| Equal opportunities (sex) | % | 100% | 100% | 100% | 100 | 100 | 100 | 5 | 5 | 5 |
| Equal opportunities (disabilities) | % | 33% | 17% | 0% | 33 | 17 | 0 | 2 | 1 | 0 |
| Children's environmental education | % | 17% | 100% | 25% | 17 | 100 | 25 | 1 | 5 | 2 |
| Local employment | % | 100% | 100% | 100% | 100 | 100 | 100 | 5 | 5 | 5 |
| Public commitments to sustainability issues | % | 100% | 100% | 100% | 100 | 100 | 100 | 5 | 5 | 5 |
| Contribution to economic development | % | 100% | 100% | 100% | 100 | 100 | 100 | 5 | 5 | 5 |
| | | | | | Total score | | | 30 | 29 | 24 |

Score negative indicators: 0–20 %=5, 21–40 %=4, 41–60 %=3, 61–80 %=2, 81–100 %=1

Score positive indicators: 0–20 %=1, 21–40 %=2, 41–60 %=3, 61–80 %=4, 81–100 %=5

**Table 3** Sustainability factors

| Total Scores | DTD | SCH | UCC | Sustainability Factors (Relative values) | DTD | SCH | UCC |
|---|---|---|---|---|---|---|---|
| $LCA_{environmental}$ | 14 | 11 | 17 | $SF_{environmental}$ | 0.82 | 0.65 | 1.00 |
| $LCC_{costing}$ | 1 | 5 | 5 | $SF_{costig}$ | 0.20 | 1.00 | 1.00 |
| $S\text{-}LCA_{social}$ | 30 | 29 | 24 | $SF_{social}$ | 1.00 | 0.97 | 0.80 |

21 % and 5 points for 20–1 %. On the other hand, for *positive indicators*, the scale of scores is: 1 point for percentage contribution of 1–20 %, 2 points for 21–40 %, 3 points for 41–60 %, 4 points for 61–80 % and 5 points for 81–100 % (see Table 2).

In order to be more arbitrary between economic indicators, in LCC scoring process, we have obtained a total cost instead of score all indicators separately (see Tables 2 and 5). The costs of $CO_2$ emissions have not been included in LCC scoring process, because these costs have been already scored in LCA.

3. After scoring all the indicators, a total score is calculated for each assessment (LCA, LCA and S-LCA). Total scores have been recalculated into relative values in order to get the same magnitude (between 0 and 1) and to compare the three collection systems and the three dimensions studied: environmental, economic and social. The relative values obtained have been named: SF, defining three sustainability factors: *SF*environ., *SF*costing and *SF*social. The values of SF are between 0 and 1, so the SF with values near to 1 contributes greatly to sustainability assessment and SF with values near to 0 contributes lower (Table 3).

## 3 Results and discussion

In the following sections, the results and discussion of the study will be presented

### 3.1 Environmental results

The results in Table 4 show that SCH system has the highest environmental impact in all categories; this is because this system requires more van more trips during the collection stage than the other systems and transport stages involve a significant environmental impact. UCC system presents the lowest environmental impacts because unlike DTD and SCH no intermediate transportation is involved in the collection stage, citizens go directly to UCC on foot.

Figure 2 shows the environmental impact categories considered, distinguishing between transport stages and the other stages not considered transport (manufacture of collection containers, manufacture or storage containers and cleaning of containers). Depending on the impact categories considered, transport contributes between 25 and 64 % in DTD, between 30 and 79 % in SCH and between 4 and 11 % in UCC. The UCO transport in DTD and SCH is carried out by a van because both systems have diffuse UCO producers and low quantities to be collected, because neither schools nor SWC can accumulate more than 500 l of UCO according to Catalan waste regulations, but maybe it could be possible to improve the frequency or the type of vehicle used.

### 3.2 Economic results

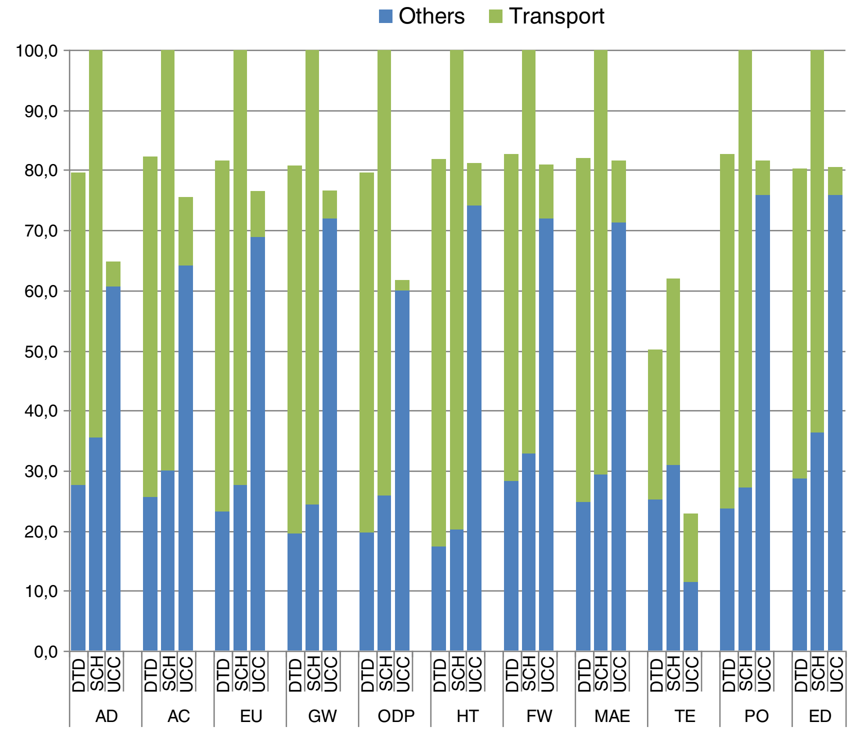
Table 5 shows the results of the economic analysis. DTD system presents the highest management cost because it requires a higher number of employees and more complex logistics. SCH system presents a higher cost in the collection container manufacture stages, because this system needs more collection containers to transport the UCO collected. SCH system also presents a higher cost in $CO_2$ mitigation because this system needs more intermediate transport stages so more $CO_2$ is emitted. UCC presents the lowest management cost because it needs fewer employees. Although the UCC has no intermediate transport involved during the collection stage,

**Table 4** LCA results

| Indicator | Units | DTD | SCH | UCC |
|---|---|---|---|---|
| AD | kg Sb eq | 55.07 | 69.06 | 44.73 |
| AC | kg SO2 eq | 26.27 | 31.91 | 24.09 |
| EU | Kg PO4–- eq | 7.82 | 9.57 | 7.34 |
| GW | kg CO2 eq | 6,875.35 | 8,510.98 | 5,651.11 |
| ODP | kg CFC-11 eq | 0.001 | 0.0013 | 0.008 |
| HT | kg 1,4-DB eq | 2,549.25 | 3,111.33 | 2,524.86 |
| WAE | kg 1,4-DB eq | 1,144.25 | 1,381.71 | 1,119.02 |
| MAE | kg 1,4-DB eq | 2,294,869.64 | 2,798,558.05 | 2,283,038.82 |
| TE | kg 1,4-DB eq | 54.93 | 58.26 | 45.55 |
| PO | kg C2H4 | 2.03 | 2.45 | 2.00 |
| ED | MJ eq | 138,146.16 | 172,189.35 | 138,708.29 |

*AD* abiotic depletion, *AC* acidification, *EU* eutrophication, *GW* global warming (GWP100) ODP, ozone layer depletion, *HT* human toxicity, *WAE* freshwater aquatic ecotox, *MAE* marine aquatic ecotoxicity, *TE* terrestrial ecotoxicity, *PO* photochemical oxidation, *ED* energy demand

**Fig. 2** Impact categories for DTD, SCH and UCC collection systems




*AD:Abiotic depletion ,AC: Acidification, EU: Eutrophication, GW:Global warming (GWP100) ODP, Ozone layer depletion, HT: Human toxicity, WAE: Fresh water aquatic ecotox, MAE: Marine aquatic ecotoxicity, TE: Terrestrial ecotoxicity, PO: Photochemical oxidation, ED: Enegy demand*

the cost of transport is higher because it generates more UCO, so more trips to the BDP are required.

### 3.3 Social results

Table 6 illustrates the results for social indicators; DTD is the system with the highest contribution in terms of the total number of employees, employees with disabilities and total working hours. The collection stage in DTD is directly done at citizens' homes and is mainly carried out by employers with special needs or a disability; all of this implies that a greater number of employees are involved, and extra coordination personnel are also necessary to support special employees. According to the results in Table 6, this system has the highest total number of employers creating 55 jobs, and also contributes to equal opportunities for employees with disabilities with 33 % and to children's environmental education with a contribution of 17 %. SCH creates 20 jobs and also hires employees with special needs but only in the storage and cleaning stages. This system has better results for raising children's environmental education than DTD and UCC with a contribution of 100 %. The SCH system

**Table 5** LCC results

| Economic cost € | DTD | SCH | UCC |
|---|---|---|---|
| Personnel | 36,104.00 | 4,360.00 | 1,587.50 |
| Transport | 231.28 | 254.06 | 260.01 |
| Collection container | 643.50 | 1,271.11 | 667.33 |
| Storage container | 756.00 | 840.00 | 882.00 |
| CO2 costs | 85.12 | 105.37 | 69.96 |
| Total cost | 37,819.89 | 6,830.54 | 3,466.81 |
| Total cost without $CO_2$ | 37,734.78 | 6,725.18 | 3,396.85 |

**Table 6** S-LCA results

| Social indicators | DTD | SCH | UCC |
|---|---|---|---|
| Total employees | 55 | 20 | 9 |
| Total working hours | 92,843 | 29,156 | 9,126 |
| Total employees with disabilities | 38 | 8 | 0 |
| Total employees with higher education | 9 | 5 | 2 |
| Total employees with basic education | 46 | 15 | 12 |
| Equal opportunities (sex) | 100 % | 100 % | 100 % |
| Equal opportunities (disabilities) | 33 % | 17 % | 0 % |
| Children's environmental education | 17 % | 100 % | 25 % |
| Local employment | 100 % | 100 % | 100 % |
| Public commitments to sustainability issues | 100 % | 100 % | 100 % |
| Contribution to economic development | 100 % | 100 % | 100 % |

also contributes to equal opportunities for employees with disabilities with 17 %. UCC presents the lowest social results, because it has the lowest number of employees, creating nine jobs and has no employees with disabilities; however, it has a good score for children's environmental education by contributing a percentage of 25 %. In UCC, different urban wastes are collected, so technical knowledge and responsibility are required to manage them; this implies difficulties to generate jobs for people with disabilities.

### 3.4 Sustainability assessment results

Table 7 and Fig. 3 shows the results of the sustainability assessment (LCSA) and the different values obtained for the SF defined.

According to the results obtained, UCC system has the best environmental performance with SF=1, followed by DTD with a SF=0.82 and then SCH with SF=0.65. Note that UCC system does not need intermediate transport so this gives to this system a high environmental SF, whereas SCH has the lowest environmental SF because this system requires more van trips and a larger number of collection containers than the other systems.

Regarding to the economic results, UCC and SCH have an SF=1 while DTD has an SF=0.20. DTD system presents lower economic SF because this system requires a higher number of employees and more transportation costs.

Concerning to the social results, DTD and SCH systems present good performance with an SF=1 and SF=0.97n respectively, followed by UCC with an SF=0.80. In UCC, different types of urban waste are collected at the same point (multi-waste collection), in consequence a low number of staff is needed to manage it, and this means that social component is weaker.

According to the results, when SF performs well in environmental and economic aspects, the social component is weaker. Environmental and economic components improve when the efficiency of the UCO collection systems improves, but in the case of social component it does not contribute favourably to the efficiency and reduces the environmental and economic components (even so, it creates jobs and provides opportunities for workers with disabilities).

**Table 7** LCSA results

| Total scores | DTD | SCH | UCC |
|---|---|---|---|
| $LCA_{environmental}$ | 14 | 11 | 17 |
| $LCC_{costig}$ | 1 | 5 | 5 |
| $S\text{-}LCA_{social}$ | 30 | 29 | 24 |
| Sustanability factors | DTD | SCH | UCC |
| $SF_{environmental}$ | 0.82 | 0.65 | 1.00 |
| $SF_{costig}$ | 0.20 | 1.00 | 1.00 |
| $SF_{social}$ | 1.00 | 0.97 | 0.80 |

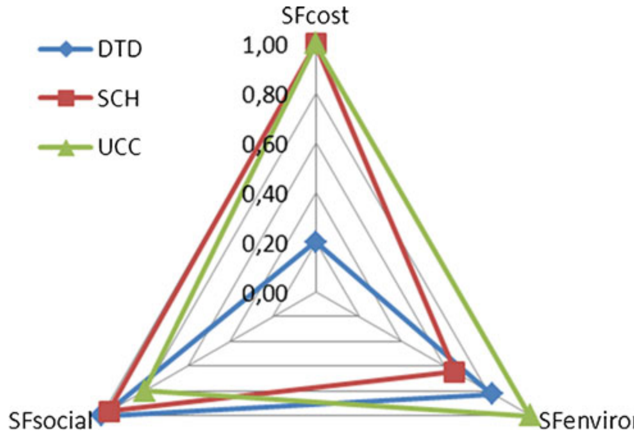



**Fig. 3** LCSA results

## 4 Conclusions

According to the results obtained, UCO collection systems that carry out a multi-waste collection service (such as UCC) are more sustainable than collection systems that only collect one type of waste. The environmental component improves if the collection points are close to citizens' homes because they can bring the UCO on foot and therefore avoid transport stages. Results obtained demonstrate that the transport stage has a high influence on the environmental component due to a non-optimised logistics of UCO collection and the use of low efficiency vehicles per unit of weight transported (see Fig. 2).

About the characteristics of the collection systems studied, note that the study gives emphasis to the motivation that each system generates to the citizens and how this affects to the amount of UCO collected. This study wants to evaluate the impact and sustainability of the UCO collection services, not the amount of biodiesel produced from UCO collected, so the production of biodiesel is not part of the he boundary of the study. This study does not want to measure the impacts avoided by not distorting the results of the impact of UCO collection services, because it does not know for sure if all the UCO collected will be used to produce biodiesel, and therefore the best system will be the one that collects more UCO with less impact, less costs and contributes better socially.

Regarding the methodology of this study, it has been observed that when SF performs well in environmental and economic aspects, then the social component is weaker, and vice versa. According to social indicators selected and in a context of developed country, environmental and

economic factors improve when the efficiency of the UCO collection systems improves; but in the case of social component, even if it has good score because it involves employees with disabilities or increase job creation, it does not contribute favourably to the efficiency of the system and reduces the environmental and economic vectors.

The LCSA method proposed in this study allows comparison among environmental, economic and social dimensions because it uses quantitative indicators, although the methodology should be improved, especially concerning the weighting process and the complexity of measuring social impacts (which impact categories to include in the assessment and how to measure social impacts) because the perception of social impacts is very variable. In order to relate social indicators and its impact to the functional unit and to confine them to a manageable and comparable number, in this study, it has been assumed that each dimension (environmental, economic and social) has the same weight, but the indicators chosen have different percentages of contribution to the global sustainability of the systems studied. So it has been distinguished between positive indicators and negative indicators, according to their contribution to sustainability in accordance with the characteristics of the systems studied. Negative indicators are those that high values have a negative contribution to sustainability (economic and environmental indicators) and positive indicators are those that have a positive contribution to sustainability (social indicators).

Mentioning that to apply the LCSA methodology proposed in this study to other systems, the scoring process and the percentages of contribution should be adapted properly according to the particular characteristics of the system studied and how the indicators chosen contribute to sustainability in order not to magnify the excessively positive or negative aspects and avoid distorting the results. For example, in LCC scoring process, $CO_2$ emissions costs have not been considered in order to avoid double counting because the $CO_2$ emissions have already been scored in LCA.

Defining units for quantifying sustainability is a difficult task because not all social indicators are quantifiable and comparable, even some need to be adapted, raising the subjectivity of the analysis. The selection of social criteria and their quantification is still a difficult task when implementing the concept of sustainability. The main problems are how to relate social indicators and its impact to the functional unit of the system and how to restrict social indicators proposed to a manageable and comparable number. LCSA requires a multi-criteria evaluation to address the balance of the indicators as well as the weighting between them. Research into S-LCA and LCSA is recent; more research is needed in order to improve the methodology and consensus for characterization and comparison between indicators.

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